

Macro Speed-Flow Model for On- and Off-Ramps on Multilane Roads

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ABSTRACT

The National Road Administration in Sweden has initiated a comprehensive research project concerning traffic on multilane roads. The name of the project is TPMA for Traffic Performance on Major Arterials. A model for four-lane road segments was presented in Copenhagen 1998. Now a macro model for Freeway On- and Off-ramps has been developed. This model is based on traffic data from twelve interchanges with several measuring spots in each interchange. Normally in Sweden the on-ramps are not regulated by any give way regulations to the main stream, instead there is an acceleration lane for the on-ramp.

The model for influence of on-ramps on the main road traffic consists of three submodels

1. Model for lane distribution of the vehicles downstream the on-ramp

This submodel calculates the numbers of vehicles just downstream the on-ramp for the right and left lane respectively, as function of the total traffic flow and the flow on the ramp. The flow in the right lane is estimated as an exponential function of the total flow together with an adjustment expression, which contains the proportion of ramp flow.

2. Model for lane capacity

The capacity value for two lanes just downstream the on-ramp is estimated as a function of the ramp flow. The model is based on traffic data from interchanges with traffic conditions varying from low to congested and with different ramp flows but with 1,000 veh/h at the most. The results indicate that there is an immediate loss in capacity of about 100–200 veh/h caused by the ramp in itself, and then the capacity is reduced by a further 25% of the on-ramp flow.

3. Model for speed-flow relationship

There is a model for speed-flow relationship for each individual lane based on the empirical data. The speed-flow curve is linear, but divided in three parts. For low and intermediate flows the curve is rather flat and it drops steeply at a v/c -ratio around 0.75–0.85. Each lane is described individually because there is a significant difference in speed level between the two lanes.

For off-ramps a model has been developed for lane distribution of the vehicles just upstream the off-ramp. The flow in the right lane is estimated as a non-linear function of the total flow and the off-ramp flow.

1. INTRODUCTION

The Swedish National Road Administration (SNRA) has commissioned the Centre for Traffic Engineering and Traffic Simulation (CTR) to conduct a major development project designated TPMA (Traffic Performance on Major Arterials). TPMA comprises the development of three models—a macromodel and two micromodels treating the driver/vehicle as one and two objects respectively. The models describe the traffic process on multi-lane roads with traffic interchanges and will provide a basis for various calculations of effects in the National Road Administration's project design and planning system.

The first stage in the macromodel entailed the development of a speed-flow model for four-lane arterials. This model consists in turn of four submodels predicting lane distribution in various traffic flows, free flow speed at various levels of road performance, capacity per lane and speed-flow relation per lane. The model for four-lane road segments was presented at the Third International HCM symposium in Copenhagen in 1998.

The general experience from Swedish arterials is that on-ramps are bottlenecks with significant lower capacity on the main road compared with a long road segment without any interchange. The second stage of the modelling work therefore consists of development of a model for on-ramps and off-ramps. This model is in turn built up from four submodels. The first is a conventional model for lane distribution, where the traffic flow in the right-hand lane is predicted by the total traffic flow just downstream an on-ramp. The capacity just beyond an on-ramp is depending of the traffic performance in both lanes and the interaction between the lanes. Therefore the second submodel gives the capacity in both lanes just downstream the on-ramp as a function of the on-ramp flow. Finally, the third submodel describes the speed-flow relation for each lane. It is necessary with a model for each individual lane depending of a significant difference in speed level between the two lanes. In addition, there is a special model for off-ramps, which predicts the flow in the right-hand lane just before the off-ramp.

This document describes the development work and the results obtained with the on-ramp and off-ramp macromodels and their submodels.

2. DATA COLLECTION

As a basis for designing the model, field measurements at interchanges have been performed during the period 1996–98 in the form of spot speed measurements in a number of sections close to and inside an interchange. The measurements made it possible to collect data for each individual lane on the main road and the ramp. At each spot the actual speed and arrival time for each passing vehicle has been measured together with registration of driving lane and vehicle type. The duration of the measurement at each spot is 30–50 hours.

A total of twelve measuring sites with on-ramps and seven with off-ramps produced acceptable measuring data. But only six interchanges (Bredden north and south, Rotebro, Rosengård, Näsby, and Norra Länken) had a traffic density so that any form of capacity limit could be achieved.

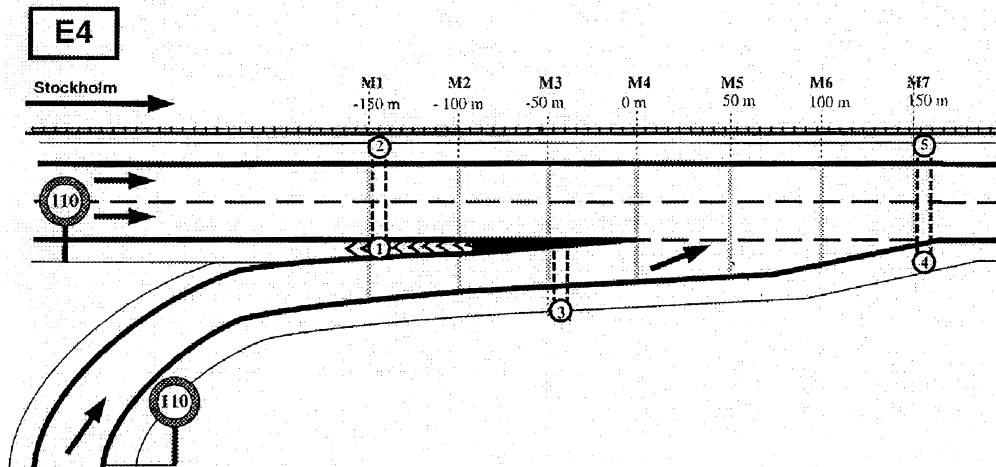


FIGURE 1 The measurement arrangement in an on-ramp site.

Figure 1 illustrates the arrangement of the measurement for an on-ramp site. Traffic data are collected in the spots numbered 1 to 5 in the figure. The vehicles on the on-ramp are merging into the main road from the acceleration lane between spots 3 and 4, with the length of 150 m.

3. LANE DISTRIBUTION MODEL

3.1 On-Ramps

3.1.1 Purpose

The submodel for lane distribution is designed to indicate the number of veh/h in the right-hand lane just beyond the on-ramp. Input data consist of the total flow after the on-ramp and the on-ramp flow. The model can be illustrated generally with the following expression:

$$rl = f(t, r)$$

where:

rl = flow in right-hand lane after an on-ramp (veh/h)

r = ramp flow (veh/h)

t = total flow (right-hand plus left-hand lane) after an on-ramp (veh/h)

3.1.2 Method

For the lane model, only the vehicle flows are analyzed. All 12 measuring sites were chosen for this model. Reliable data from five measuring points are available for almost all these measuring sites: flows before the on-ramp for the right-hand and left-hand lane, respectively; flows after the on-ramp for the right-hand and left-hand lane, respectively; and flows on the ramp. All but three measuring sites are performed with an acceleration lane and in the other three a ramp vehicle has to give way for the main road traffic.

When designing the lane distribution model for flows after on-ramps, calculations were made for each 60-minute period of flow in the right-hand lane and left-hand lane respectively, as well as total flow and ramp flow. For each new 5-minute period, a new 60-minute period was calculated. This is because it is desirable to get as many full 60-minutes periods as possible. This method gives 12 values per hour. Consequently, there is a strong dependence between observations lying close to each other in time. The disadvantage is that normal statistical tests, as the t -test, are not applicable because the observations are not independent.

Input data to the model are thus limited to two variables; total flow and ramp flow. The intention is to find a suitable function expression that explains the variations in the flow for the right-hand lane after an on-ramp as satisfactorily as possible. The function expression must be simple, with low residuals and with a logical appearance. Figure 2 illustrates the relation between the flow in the right-hand lane and the total flow after the on-ramp. The example is taken from the Rotebro site outside Stockholm with an on-ramp flow between zero and 350 v/h.

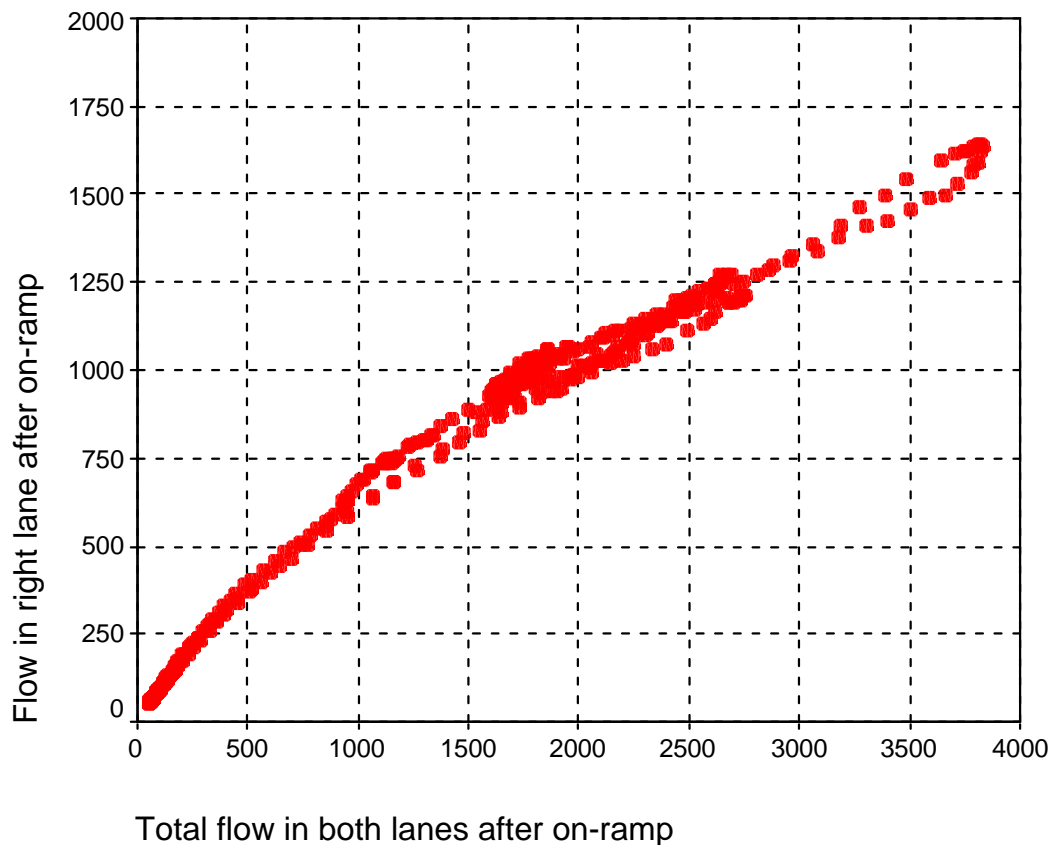


FIGURE 2 Traffic flow (v/h) in right-hand lane after on-ramp as a function of the total flow (v/h) in both lanes.

Ten different model designs were tested (see table below). The tested designs have the following mathematical expressions:

a, **b**, **c** and **d** are parameters. **RL** (traffic flow in right-hand lane), **T** (total flow in both lanes after an on-ramp), and **R** (traffic flow on the on-ramp) are variables.

1. $RL = a + b \cdot T + c \cdot R$
2. $RL = a + b \cdot T^c + d \cdot R$
3. $RL = a + b \cdot T + c \cdot R + d \cdot R \cdot T$
4. $RL = a + b \cdot T + c \cdot R + d \cdot R^{0.5} \cdot T$
5. $RL = a [1 - \exp(-b \cdot T)]$
6. $RL = a [1 - \exp(-b \cdot T)] \cdot (1 + R/T)^c$
7. $RL = a [1 - \exp(-b \cdot T)] \cdot (1 + R^c/T)$
8. $RL = a [1 - \exp(-b \cdot T)] \cdot [1 + (R/T)^c]$
9. $RL = a \cdot T + R + b \cdot R^c \cdot T$
10. $RL = R + a [1 - \exp(-b \cdot T)] \cdot \exp(-c \cdot R/T)$

The model to be finally chosen as “best” must have a low sum of residual squares, and furthermore it must be logical. This means that the appearance of the model must be simple and logically defensible, and also that it must be statistically logical. In other words, the residuals, the difference between observed and predicted values, must be independent of the predicted value. Since there are no independence between the points normal statistical tests like *t*-tests are irrelevant.

In addition, the model should contain an interaction term since for high ramp flows a relatively large part of the main road flow is shifting from the right-hand lane to the left-hand lane immediately before the on-ramp. This behavior has been observed from the measurements in high flow traffic times.

3.1.3 Choice of model

The model with the lowest sum of residual squares at the most of the measuring sites is model (7), which has the following general appearance:

$$RL = a [1 - \exp(-b \cdot T)] \cdot (1 + R^{**c}/T)$$

The model is an expansion of the four lane road model in Carlsson and Cedersund (1998), which can be said to confirm the relation in behavior between the multi-lane model and the on-ramp model.

The result from data processing of the complete material is a calculated value of the parameter **c** of 0.995. Since the difference between **R** and **R**^{0.995} only is 5 per thousand and the influence on the model is less than 2%, **c** can be set equal to 1, i.e., it can be ignored.

The final model will have the following appearance after regression of the complete data material. The *R*²-value is very high (not far from 1) but that is irrelevant because the observations are not independent.

$$RL = 1800 [1 - \exp(-0.00039 \cdot T)] * (1 + R/T)$$

3.2 Off-Ramps

3.2.1 Purpose

In a similar way as for on-ramps, the submodel based on an hourly level is designed to predict the number of vehicles in the right-hand lane just before the on-ramp as a function of the flow in both lanes and the off-ramp flow.

3.2.2 Method

When working on the lane distribution model before an off-ramp, calculations are made for each 60-minute period of flow in the right-hand and left-hand lanes, as well as the total flow and ramp flow. For each new 5-minute period, a new 60-minute period is calculated, giving 12 values per hour, in the same way as for the on-ramp model. A number of models were tested in a similar way to the procedure for the on-ramps.

But off-ramps seldom cause disturbances and interactions in the same way as on-ramps. In designing the multi-lane road model, it was found that capacity was significantly higher for outbound traffic from towns compared to inbound traffic towards a city center. The explanation seems to be the presence of on-ramps with high traffic flows towards the center and just off-ramps from the center. An off-ramp is seldom experienced as a traffic bottleneck. It is possible that drivers have a higher speed and a shorter time gap to a turning off vehicle in front since they expect the off-ramps to create space further ahead. The work on models for off-ramps is therefore somewhat more summary than the work on the on-ramp models.

The following eight models were tested. (Nos. 1–8 among the on-ramp models tested. None of the designs is specific for off-ramps.)

1. $RL = a + b \cdot T + c \cdot R$
2. $RL = a + b \cdot T^c + d \cdot R$
3. $RL = a + b \cdot T + c \cdot R + d \cdot R \cdot T$
4. $RL = a + b \cdot T + c \cdot R + d \cdot R^{0.5} \cdot T$
5. $RL = a [1 - \exp(-b \cdot T)]$
6. $RL = a [1 - \exp(-b \cdot T)] * (1 + R/T)^c$
7. $RL = a [1 - \exp(-b \cdot T)] * (1 + R^c/T)$
8. $RL = a [1 - \exp(-b \cdot T)] * [1 + (R/T)^c]$

a, **b**, **c** and **d** are parameters. **RL** (traffic flow in the right-and lane just before the off-ramp), **T** (total flow in both lanes before the off-ramp), and **R** (traffic flow on the off-ramp) are variables.

3.2.3 Choice of model

Model (4) has the lowest sum of residual squares at the largest number of the measuring sites. This is chosen as the best model for off-ramps.

$$RL = a + b*T + c*R + d* R^{0.5}*T$$

The calculated parameter value for **a**, the constant in the equation above, is almost zero and is omitted from the equation.

The parameter **c** for **R** is considerably larger than 1. The number of vehicles in the right-hand lane thus increases by more than 100% of the number of ramp vehicles, which may seem paradoxical. The explanation may be that vehicles driving straight ahead exploit the fact that many vehicles turning off will create space further ahead and therefore decline to change to the left-hand lane.

After regression, the final form for the off-ramp model is described below. The R^2 -value is very high as for the same reason as for the on-ramp model.

$$RL = 0.643*T + 1.42*R - 0.017* R^{0.5}*T$$

4. CAPACITY MODEL

4.1 Purpose

The capacity just beyond an on-ramp is depending of the traffic performance in both lanes and the interaction between the lanes. There is a significant changing of vehicles from right to left lane inside the interchange area. Therefore the second submodel gives the capacity in **both** lanes just downstream the on-ramp as a function of the on-ramp flow.

$$C_i = f(r)$$

C_i = capacity in both lanes after the on-ramp

4.2 Method

Most of the on-ramps have been chosen because they could be expected to reach a capacity maximum. Even if a weak but clear speed-flow influence can be distinguished for almost all sites, surprisingly only six road segments have a clearly observable capacity value in both right-hand and left-hand lanes after the on-ramp. These were used to create a capacity model. But one of these sites was taken away to be used as a site for a small validation.

Modelling of the capacity relation has used 5-minute observations converted to hourly flows. These 5-minute periods have been calculated for the right-hand and left-hand lanes and the on-ramp at the same time. The flows have been plotted in graphs as a function of time. In the final analysis, flow and speed were plotted for 5-minute periods at the same time for the right-hand and left-hand lane and the on-ramp. These flow data were plotted against time to give simultaneous observations of the flow in the three lanes. Below, the capacity is assumed to be the highest measured 15-minute flow, i.e., three consecutive 5-minute periods converted to hourly flow. Thus, two values were obtained from each on-ramp site since the measurements were carried out for two full days. As a rule, the

maximum flows occurred immediately before a significant decrease in speed and flow. Consequently, a total of 10 capacity values were obtained. Entering these 10 values in a graph with the simultaneous ramp flow gives the following Figure 3. Acceleration lane length and posted speed are presented in the caption text to the figure.

The values from two days and the same measuring site are interconnected. A normal origin on the x-axis for a four lane road, i.e., an arterial without any on-ramp flow to take into consideration, should be in the range of 4,200–4,400 vehicles per hour on the y-axis in the graph. In view of the uncertainty in this assumption, it seems that the initial capacity loss after an on-ramp is in the size of 100–200 vehicles per hour compared with a road segment without an on-ramp.

With exception of one site it seems that there is a weak relation in the diagram between capacity and the ramp flow. It can be assumed that the capacity loss can be of about 25 vehicles per 100 ramp vehicles. However, neither the length of the acceleration lane nor even the speed limit appears to indicate any clear connection with the capacity. At all measuring sites except Rosengård, the maximum values in the right-hand lane are lower than 1,900 vehicles/h. At Rosengård, approximately 2,100 vehicles/h were recorded in the right-hand lane at the most.

In view of all uncertainty in this assumption, a macromodel for capacity in both lanes beyond the on-ramp could be:

$$\text{Capacity} = 4,150 - \text{on-ramp-flow}/4 \text{ (veh/h)}$$

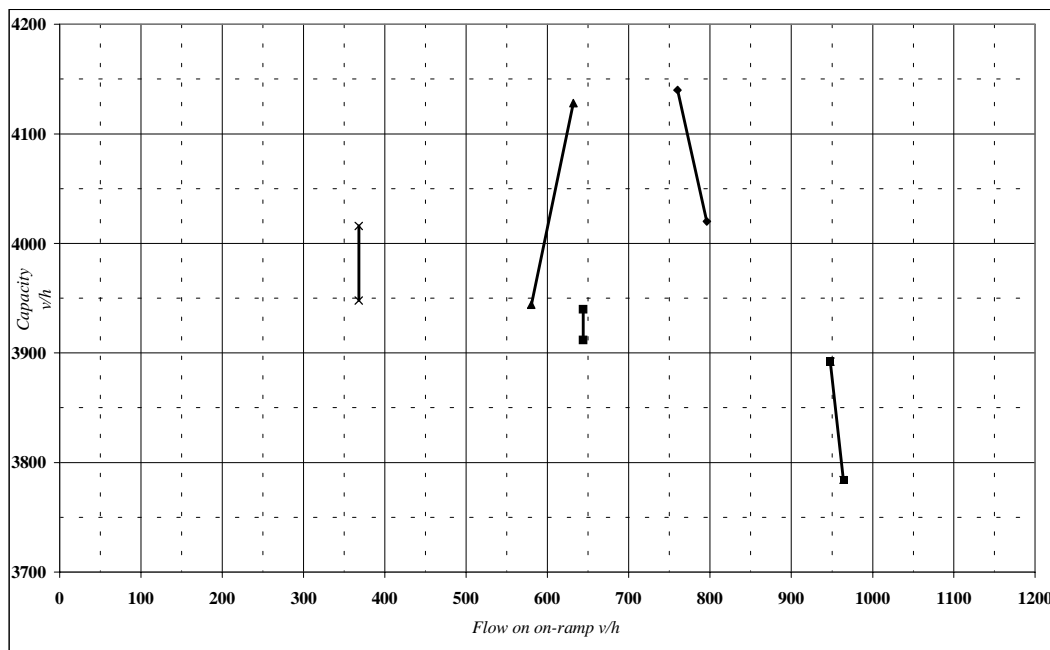


FIGURE 3 Maximum flow values, “capacity values,” plotted against simultaneous ramp flows for (from left) Rotebro (350 m, 110 km/h), Näsby (250 m, 90 km/h), Norra Länken (150 m, 70 km/h), Bredden south (150 m, 110 km/h), and Rosengård (220 m, 90 km/h).

A small validation of the model was done against data from the sixth site, Gubbängen with high ramp flows. Two days of observation gave ramp flow of 1,372 and 1,216 vehicles per hour at the capacity. Prediction from the model, with an assumed capacity of 4,150 v/h with zero ramp-flow, gives capacity on the main segment just beyond the ramp of 3,800 and 3,850 v/h, respectively. Observed values were 3,820 and 3,850 v/h, which is a fairly good agreement.

5. SPEED-FLOW MODEL

5.1 Purpose

For a given degree of saturation, the submodel for the speed-flow relation must indicate the expected speed of passenger cars on the main road just beyond the on-ramp. The relation is expressed as linear portions in three intervals for degree of saturation. The first interval has the free flow speed with no speed reduction in the interval. In the intermediate interval, flow dependence is weak and in the last interval flow dependence is significant and the speed approaches that one at capacity (degree of saturation equal to 1).

5.2 Method

There are only a few sites where increasing flow was observed to have a significant influence on speed. In other words, it is difficult to distinguish not only flow dependence but also the capacity values and traffic performance at oversaturated condition. Despite momentarily very high flows, several interchanges with on-ramps have no strong speed-flow dependence.

There are six sites with such a pronounced speed-flow relation of this type after the on-ramp that an analysis is worthwhile. A number of speed-flow plots have been made for each on-ramp. Each point in these plots represents 200 cars plus the heavy vehicles passing within the same time interval as the cars.

The speed-flow plots are used to estimate the capacity limit, speed at the capacity limit, free vehicle speed and the position of the interval limit in the speed-flow relationship. There is an obvious systematic difference in speed between the sites, but inside one site the variation in speed is low so that the speed-flow relationship could be observed. The first breakpoint is defined as the point when the free flow speed no longer applies but is replaced by a weakly sloping speed-flow relation. The second breakpoint is defined when the speed-flow relationship changes from being slight to a significant decrease in speed towards the speed at the capacity.

The speed at the capacity limit is very difficult to estimate. Primarily, a visual observation is made to estimate capacity, where the speed-flow relation changes towards lower flows with decreasing speeds. The estimated speed at capacity corresponds to about 70–80% of the free flow speed for cars.

In the following table, all values for flow have been converted to degree of saturation and for speed as a proportion of free flow speed. This gives the breakpoints expressed in relative units for each speed limit of the road segment. The table represents the average of

all sites. In a comparison between the speed limits, occasional anomalies have been adjusted to obtain logical relations between the values for different speed limits.

A final result of the above work is described in the following table, which shows the speed flow relationship for cars. The table presents flow per lane in degree of saturation (dos) and speed in percent of the free flow speed for cars. There are four lines in the table for every speed limit. Line 1 is the free flow speed (dos = 0), line 2 the first breakpoint, line 3 the second breakpoint and line 4 is the capacity limit.

The average free flow speeds for cars for each speed limit and lane are also presented in the table. In the four lane road model there was a difference between left and right lane in dos and speed level. But here in the on-ramp data there is no significant differences between the lanes and therefore the values are the same for both lanes for every posted speed.

In general, the relative values are somewhat higher than the corresponding values for multi-lane segments. The observed free flow speeds, which are based on data from six interchanges with on-ramps, are somewhat lower than for an road segment at 90 km/h, approximately equal at 110 km/h and somewhat higher at 70 km/h. However, no conclusions can be drawn from this.

TABLE 1 Speed-Flow Relationship for Three Speed Classes Given in Relative Values

| Speed limit and Free flow speed for cars | Cars | | | |
|--|------------------------|-------------------|------------------------|-------------------|
| | Left lane | | Right lane | |
| | % degree of saturation | % free flow speed | % degree of saturation | % free flow speed |
| 110 | 0 | 100 | 0 | 100 |
| | 45 | 100 | 45 | 100 |
| | 75 | 90 | 75 | 90 |
| | 100 | 72 | 100 | 72 |
| 90 100/90 km/h | 0 | 100 | 0 | 100 |
| | 45 | 100 | 45 | 100 |
| | 75 | 90 | 75 | 90 |
| | 100 | 73 | 100 | 73 |
| 70 85/75 km/h | 0 | 100 | 0 | 100 |
| | 45 | 100 | 45 | 100 |
| | 75 | 90 | 75 | 90 |
| | 100 | 76 | 100 | 76 |

6. RESULTS AND COMMENTS

6.1 Lane Distribution Model

6.1.1 On-Ramps

The final model for on-ramps thus has the following appearance:

$$\mathbf{RL} = 1800 [1 - \exp (-0.00039*\mathbf{T})] * (1 + \mathbf{R}/\mathbf{T})$$

RL is the traffic flow in the right-hand lane just after the acceleration lane for an on-ramp, **T** is the total flow in both lanes after the on-ramp, and **R** is the flow on the on-ramp.

The model contains a constant, 1,800 v/h, which do not reflects the capacity as in the multi-lane model. Then there is an initial correction term which is always less than 1, and finally a correction term which is always greater than 1. The strength of the model is that it is very simple and uses only two parameters and two variables.

Like all similar models, it is adapted to the average, i.e., it operates best in “normal” flows, although the flow in the right-hand lane, **RL**, is zero if the total flow is zero. However, the first vehicle is expected only to 70% to be in the right-hand lane. Similarly, it is difficult for the model to predict higher **RL** than 1,750 v/h, which seems to be a considered disadvantage. With a fixed value of -0.00039 from the regression, **R** must be 1,400 and **T** 4,250 v/h if **RL** should be able to attain a capacity value for right lane of 1,900 veh/h. It seems that parameter **b** must be allowed to vary with the total flow in order to obtain more realistic values of **RL** at lower values of **R**.

6.1.2 Off-Ramps

The best function expression for reflecting the flow in the right-hand lane before an off-ramp as a function of the total flow and off-ramp flow is:

$$\mathbf{RL} = 0.643*\mathbf{T} + 1.42*\mathbf{R} - 0.017*\mathbf{R}^{0.5}*\mathbf{T}$$

RL is the traffic flow in the right-hand lane before the off-ramp, **T** is the total flow in both lanes before the on-ramp, and **R** is the flow on the off-ramp.

This model also has the advantage of simplicity. **RL** is zero if **T** and **R** are zero, and the growth at lower total flows is 64% of the total traffic in the right-hand lane. It is somewhat easier for the model to predict higher values for **RL** than for the on-ramp model.

6.2 Capacity Model

Capacity over both lanes after an on-ramp appears to have an initial loss by approximately 100–200 veh/h compared with a straight road segment. In addition, capacity appears to decrease by about 25 vehicles for each 100 veh/h on the on-ramp. It is impossible to say

whether the relation is linear or non-linear. For example, it may be that the existence of an on-ramp reduces the capacity in one stage by 100–200 vehicles/h and that the relationship then is linear, at least at ramp flows above 300 veh/h. Alternatively, the relation may be non-linear with capacity values close to a road segment at very low on-ramp flows, and where the capacity decreases in a more rapid slope in a complex relationship. Both alternatives are more or less equally probable.

But the chosen linear model gives a good agreement with observed values at validation in one site.

6.3 Speed-Flow Model

The final form of the speed-flow model is illustrated in the following figure. The figure shows the speed for cars in left hand and right hand lane at three different posted speeds. The model presents the average speed for cars and for all sites just beyond the on-ramp. The difference in speed between different sites is significant, but in each different site the speed difference between observations with the same flow is small.

Naturally, it is unsatisfactory to build up a model with so little empirical data as here, especially since the model is to apply to three classes of speed limit. In particular, the free flow speeds are the result of an average from rather few sites for each posted speed. The shape of the speed flow relationship is more accurate. However, the estimated values can be further corrected with data from the multi-lane model.

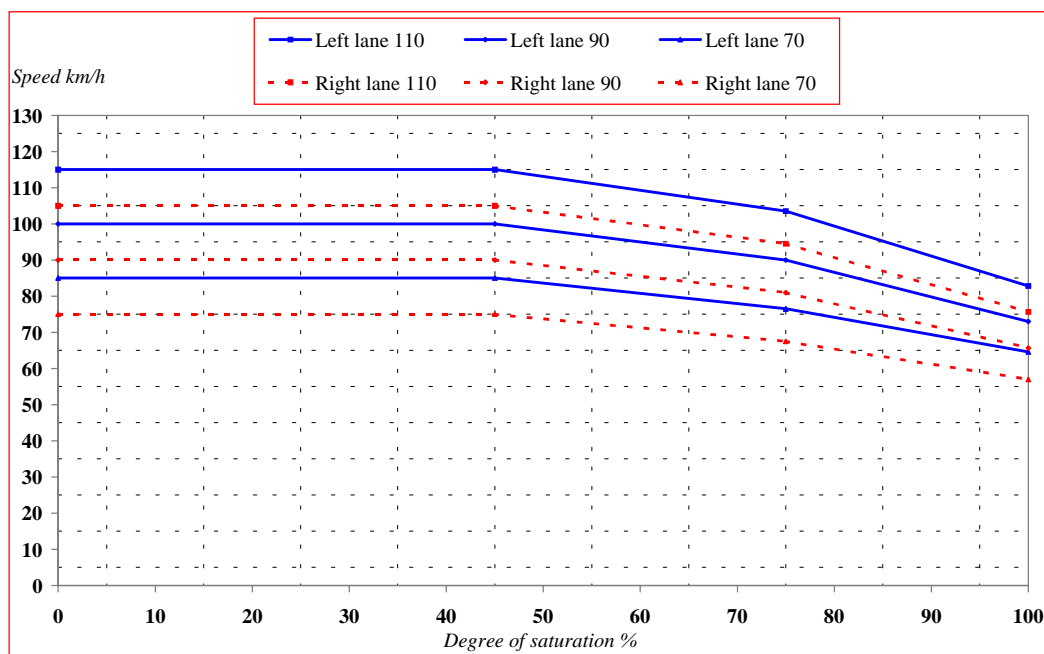


FIGURE 4 Speed-flow model for the left and right lane after the on-ramp for three posted speeds.

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